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APPENDIX M

Technical Reports

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Appendix M - Technical Reports

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Ground Vibration at Mayo Clinic Magnetic Resonance Imaging Systems

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GROUND VIBRATION AT MAYO CLINIC

MAGNETIC RESONANCE IMAGING SYSTEMS

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INTRODUCTION

The DM&E Railroad proposes to upgrade track and introduce unit coal trains from the Powder River Basin through Rochester, Minnesota. The upgrade would include replacement or addition of track with continuous welded rail. Train speeds would be increased from the current 15 mph to approximately 45 mph. The Mayo Clinic has raised concerns about ground vibration impacts resulting from unit train operations on existing and planned magnetic resonance imaging (MRI) systems. This report concerns measured vibration at the Mayo Clinic's Charlton building, produced by existing train operations, and comparison with GE Medical Systems' site specifications for MRI's.

The results of these measurements indicate that existing ground vibration levels due to trains are very low, yet just within the site specification for the latest GE Medical Systems 0.7 Tesla MRI. Random background ambient vibration levels are within the specification, but background discrete frequency vibration from building mechanical equipment are slightly in excess of the specification. The measurement locations, instrumentation, analysis procedures, and results are summarized below.

Measurements were also conducted at Lake City at an existing site for a portable MRI. This MRI is mounted on a truck trailer and parked in a lot during days when it is used. Much higher vibration levels were observed at the Lake City site than at the Rochester site, with an entirely different spectral characteristic, and the difference is believed to be due to differing soil conditions from the shallow rock found at the Mayo Clinic campus in Rochester. Therefore, the ground vibration at the Lake City site are considered non-representative of the vibration that would occur in Rochester, and are not reported here.

SITE SPECIFICATIONS

A number of MRI's are used at the Mayo Clinic campus in Rochester. An example is the GE Medical Systems Signa 1.5 Tesla LX with magnet identified as a 1.5TLCC or S3. A new GE Medical Systems OpenSpeed 0.7 Tesla MRI is planned for installation, and is specifically designed to accept patients that cannot be examined with the usual type of MRI. A GE Medical Systems 3.0 Tesla machine is being considered for installation also.

Site specifications for the 0.7 Tesla and 3.0 Tesla MRI's were obtained from the report entitled "Vibration Assessment of Proposed 0.7T and 3.0T MRI Sites at Mayo Clinic, Site Visit No. 2", by STS Consultants, Ltd., and are summarized below for various frequency ranges:

Table 1 Acceleration Limits for GE Medical Systems OpenSpeed 0.7 Tesla MRI

Acceleration Limit – micro-g	Frequency Range – Hz
1	0 to 7
10	7 to 11
5	11 to 15
25	15 to 38
15	38 to 50

Table 2 Acceleration Limit for GE Medical Systems 3.0 Tesla MRI

Acceleration Limit – micro-g	Frequency Range – Hz
10	0 to 50

Additionally, the specifications limit transient acceleration to 500 micro-g. The frequency range used for the assessment of transient acceleration was assumed to be 1 to 200 Hz.

The acceleration limits for the 1.5 Tesla MRI's at the Mayo Clinic were not provided for this report. However, specifications obtained for other GE Medical Systems Signa 1.5 Tesla MRI's were reviewed, and one of the most recent is summarized below.

Table 3 Example Specification for GE Medical Systems Signa 1.5 Tesla MRI (SIGNA MRI PRE-INSTALLATION, Direction 2223170, Rev. 0)

Acceleration Limit – micro-g	Frequency Range – Hz
10	0 to 15
50	10 to 30
10	30 to 38
200	38 to 45

Again, the transient acceleration limit for this MRI is 500 micro-g.

MEASUREMENT LOCATIONS

Two measurement locations at the Mayo Clinic Charlton building are identified in Figure 1. Location 1 was at the soil surface of an excavated area being prepared for the new 0.7 Tesla MRI. Location 2 was in a closet on a concrete slab floor near an existing MRI. This location was chosen because the there was no floor covering which had to be removed to mount the accelerometers.

The north wall of the facility is approximately 900 feet from the DM&E Railroad track.

INSTRUMENTATION

The measurement instrumentation included high sensitivity accelerometers and WIA charge amplifiers at Location 1 and high sensitivity seismic accelerometers at Location 2. The analog acceleration data were amplified and recorded on a multi-channel digital magnetic tape recorder. Tri-axial data were collected. The bandwidth of the recordings extends from approximately 0.3 Hz to 5,000 Hz, though the mounted resonance frequencies of the accelerometers limits these responses to approximately 25 Hz at Location 1 and 500 Hz at Location 2.

PROCEEDURE

The high sensitivity accelerometers were mounted on aluminum spikes driven into the soil at the location for the new 0.7T machine. The seismic accelerometers were attached to the concrete floor slab with wax.

Samples of ambient vibration data were recorded, including random background vibration and building vibration caused by mechanical equipment.

Data for two train passages were obtained, one eastbound, the other westbound. The westbound train consisted of 115 cars pulled by 3 locomotives. The first 15 cars carried lumber and building supplies. The remaining were empty. At three quarters of the way, slack action occurred in the train movement, producing some transient ground vibration. The second train consist included 67 loaded cars pulled by 3 locomotives. Many of the cars were loaded with grain.

One person was stationed at the grade crossing closest to the Charleton building to observe the type of train and speed, and to notify by radio a second person in the Charleton building when the train reached the grade crossing.

The data were analyzed at the laboratory, using procedures outlined in the GE specification for site characterization. Specifically, the data were analyzed with a Fourier analyzer using a 50 Hz analysis range and 400 lines or frequency components. A Hanning weighting function was used during spectral analysis, as specified. The resulting effective noise bandwidth of each frequency band was 0.19 Hz. The spectral data were plotted with custom software, and compared with the site specifications.

Time domain digital data were obtained directly from the data recorder and plotted with a plotting software package as amplitude versus time, using dots to represent each reading. The time domain data from the recorder were decimated to 1 in 24 samples, corresponding to a bandwidth of about 200 Hz. A decimation filter was employed prior to decimation. The resulting plots cover sample durations of approximately 300 seconds, or five minutes. The plus and minus 500 micro-g amplitude limits are also plotted for comparison.

RESULTS

Ground vibration spectra obtained at Location 1 are presented in Figures 2A through 2C. Figure 2A is of ambient ground vibration. The discrete frequency components shown in the spectra are probably caused by rotating or reciprocating mechanical equipment, though the specific sources were not identified. Figures 1B and 1C illustrate the ground vibration recorded during the eastbound and westbound train passes, respectively. The data obtained for the trains are very similar to the ambient ground vibration, though the train vibration is higher than the ambient from about 5 Hz to 25 Hz, neglecting the discrete frequency components caused by the mechanical equipment. Corresponding data measured at Location 2 are presented in Figures 3A, 3B, and 3C. The train vibration at Location 3A exceeds the ambient ground vibration by roughly 10 decibels at frequencies below 10 Hz.

Specifications for various GE MRI's are also plotted in Figures 2A, 2B, 2C, 3A, 3B, and 3C. The most restrictive specification is the one shown for the 0.7 Tesla MRI, while the least restrictive specification is one that was applied in 1998 to GE 1.5 Tesla MRI's. The intermediate specification is for the 3.0 Tesla MRI that may or may not be installed at the Mayo Clinic. The ambient vibration data were within the specifications, except for discrete frequency components that are likely due to mechanical equipment within the building. The train vibration data appear to be within the specifications. The discrete frequency components observed during train passage were related to those appearing during the ambient samples, and are thus not attributed to the trains. For example, during passage of the eastbound train, an additional discrete frequency component was observed at about 27 Hz, and as shown in Figures 2A and 3A. This component is in excess of the specifications, but is not due to the train. The component appears in the background data obtained at Location 2, as shown in Figure 3A.

The horizontal vibration observed at each location exceed the vertical component of vibration. The excess is of the order of 10 dB, or a factor of 3 in amplitude. This is a surprising result that is not usually observed, but may be related to the shallow nature of the surface soil, in which transverse shear waves (SH) may be more easily propagated than vertically oriented combined dilatational and shear waves (PSV waves). The effect is observed at both locations, but less so at the concrete slab location. At the concrete slab, the horizontal components are attenuated by the in-plane stiffness of the concrete slab.

At Location 2, the high frequency vertical component of vibration greatly exceeds the horizontal components. In this case, the slab appears to be easily excited by high frequency vertical ground vibration, but resists horizontal motion. In any case, the high frequency ground vibration appears to be unaffected by the trains.

Transient vibration data collected during the westbound unloaded train are presented in Figures 4 and 5 for Locations 1 and 2, respectively. The vertical, transverse, and longitudinal directions are represented. The transient data are for a single event, and are believed to be caused by slack action of the train. At Location 1, the maximum magnitude of vertical acceleration was about 700 micro-g. At Location 2, the maximum magnitude of vertical acceleration was between 1,300 and 1,500 micro-g. The horizontal components of vibration were within the 500 micro-g limit at both locations.

Time domain acceleration data collected at Location 1 over periods of 30 seconds are plotted in Figures 6A and 6B for the ambient and passing eastbound train conditions. These data were obtained simultaneously with the data collected at the slab at Location 2. Except for a short transient event, the ambient acceleration magnitudes were within the plus and minus 500 micro-g limits.

During train passage, the acceleration magnitudes shown in Figure 6B were within the plus or minus 500 micro-g limits. At about 140 seconds into the sample, the vibration magnitude drops suddenly, thereafter remaining constant. The higher level occurring at the beginning of the sample is similar to the magnitudes occurring during the end of the preceding ambient sample. The train vibration sample was begun at about the same time as when the train reached the grade crossing nearest the measurement location. The passby duration is estimated to be 318 seconds, assuming a car length of 60 feet for all 67 cars and 3 locomotives traveling at 9 mph. Thus, the drop in magnitude at 130 to

140 seconds into the sample is not explained by train vibration cessation, and may be due to cessation of some piece of mechanical equipment in the building. Regardless, the train vibration data were not in excess of the limits.

Time domain acceleration data collected at Location 2 are plotted in Figures 7A and 7B for the ambient condition prior to arrival of the loaded eastbound freight, and during passage of the loaded eastbound freight, respectively. This location was at the concrete slab. The vertical component of vibration was significantly greater than the horizontal components. These ambient data contain samples that exceeded the 500 micro-g limits, but then only relatively infrequently. During the middle of the ambient sample, a piece of mechanical equipment produced increased levels of vertical vibration for approximately 30 seconds. Also, at the beginning of the increased ambient vibration, a short duration transient produced and acceleration with magnitude of approximately 1,000 micro-g in the vertical direction, and lesser magnitudes in the horizontal direction. The same short transient acceleration occurs at about 110 seconds into the ambient sample that was observed at Location 1 and presented in Figure 6A.

During train passage, the vibration data collected at Location 2 were steady. There was some evidence of vibration transients exceeding 500 micro-g during passage, but the number of exceedances is not significantly different from that of the ambient sample obtained without the anomalous building vibration.

The passage of the eastbound train was not apparent in the vibration data monitored by the test engineer within the Charlton building, though there was a faint audible train horn noise in the signal from the vertical accelerometer mounted on a spike driven into the soil at Location 1. The transmission path for this was not identified, but is likely related to airborne excitation of the building structure and ground.

PREVIOUS REPORT BY STS CONSULTANTS, LTD

The report entitled "Vibration Assessment of Proposed 0.7T and 3.0T MRI Sites, Site Visit No. 2" by STS Consultants, Ltd, was reviewed prior to the measurements reported here. In that report, data are indicated for train passbys that exceeds the specification for the 0.7T and 3.0T MRI's. The report indicated that switching operations produced a discrete frequency vibration component at 31 Hz, and that a through freight generated a discrete frequency vibration component at 35 Hz. The vibration produced by trains is usually characterized by random vibration with a broad peak at perhaps 10 to 50 Hz, depending on the soils and distances involved. Discrete frequency peaks are usually generated at lower frequencies for low speed trains, and are related to wheel rotation, wheel passage rates, and, some believe, tie spacing. The discrete frequency peaks referred to in that report appear to be consistent with vibration from mechanical equipment. There is the possibility that the peaks are produced by the locomotive exhaust. The accelerometers were mounted in a flower box located outside of the Charlton building, and was necessarily exposed to airborne noise from the locomotive exhaust. The response of the accelerometers may have been caused by airborne noise excitation of the flower box in which the accelerometers were placed. If so, it is unlikely that similar vibration would be observed within the Charlton building, except at much lower magnitude.

PROJECT VIBRATION LEVELS

The vibration from coal operations will likely differ from those measured here. The reasons include: 1) upgrading of track to continuous welded rail, and 2) increased train speed. Upgrading of track to continuous welded rail may be expected to produce a 6 to 10 dB reduction of ground vibration, depending on the quality and straightness of existing track. However, increasing the train speed may be expected to increase vibration levels. A conservative assumption is that vibration levels increase by 6 decibels per doubling of train speed, corresponding to a doubling of train vibration amplitude for each doubling of train speed. Often, only a shift in peak frequencies is observed, with only a modest increase in vibration. In some cases, above certain frequencies, little or no increase in vibration has been observed with increasing train speed.

The existing ground vibration spectra observed for the eastbound and westbound trains indicate a broad peak between about 14 and 18 Hz. The amplitude and frequency of this peak will likely shift upward with increasing train speeds. The vibration at Location 1 would likely remain within the specification for the 0.7 Tesla MRI, but might exceed the limit given for the 3.0 Tesla MRI, not with standing the beneficial effects of continuous welded rail. At Location 2, the vibration would likely remain within both specifications. None of the project vibration would likely exceed the specification for the 1.5 Tesla machines shown in the figures.

There likely exist low frequency components of train vibration below 10 Hz. The frequencies of these components would increase linearly with increasing train speed. Thus, components of vibration that may exist at 5 Hz at 15 mph might appear at 15 Hz for a 45 mph train speed. Predicting the amplitude of the components is difficult without resorting to additional testing with trains operated at higher design speeds, which is not considered practical at present.

The transient acceleration caused by slack action would likely remain unchanged in magnitude after upgrading of track. While increasing the number of trains per day would be expected to increase the number of slack action events, slack action would probably not occur on a regular basis if train speed were maintained constant or varied only slightly during passage. The occurrence of slack action might actually be less after completion of the project than before if relative high train speeds of are maintained. Slack action effects appear to most apparent when the train is accelerated from stop, though slack action might reasonably be expected with acceleration or deceleration of the locomotive at any train speed. However, at higher speeds, the deceleration rates may be less, due to the amount of energy that must be dissipated per unit time, thus reducing the effect of slack action at higher speeds. Further, the generation of slack action may be dependent on the train's engineer. More investigation is needed to determine the significance of slack action at higher train speeds.

MITIGATION MEASURES

Mitigation measures include installation of the MRI on a concrete slab foundation that is supported on piles extended into the rock formation. This will attenuate vertical vibration, though existing and project vertical vibration would likely be within the specification regardless.

A concrete slab tends to reduce the horizontal vibration, due to the shear stiffness of the slab. The horizontal vibration measured at Location 1 would likely be reduced. The vertical component of vibration at frequencies below 50 Hz would likely be unaffected by a slab. Such a slab would be poured to support the MRI in any event.

Pressure grouting the soil that supports the MRI could be explored to increase the soil stiffness and thus reduce its response to rock motion.

Mounting the MRI on a concrete pad of thickness about 2 feet, and supporting the pad with augured piles that extend into the rock formation would reduce the vertical component of vibration, as well as help to reduce rotation or rocking. Mounting the MRI on a very thick concrete block would not be appropriate, as this might tend to increase ground vibration at low frequencies.

Continuous welded rail manufactured to a vertical straightness specification of +/- 0.015" in any 10 ft segment can help to control ground vibration from unit trains. Such rail is employed in Europe for high speed train systems. Rail manufactured to the above straightness specification historically has not been available from domestic mills. Rather, the rail would probably have to be procured from foreign manufacturers such as British Steel or Sydney Steel.

Most rail manufactured today is straightened with a roller straightener, which may leave periodic undulations of substantial magnitude in the rail. The older method of gag-press rail straightening may actually produce lower levels of ground vibration than roller straightening, because gag pressing produces a random rather than coherent distribution of vertical surface undulations. Coherent vertical rail undulation such as may be caused by a roller straightener may cause a high ground vibration radiation efficiency for the track, thus leading to higher levels of ground vibration than would otherwise be the case. The straightness specification indicated above would help to control this effect, though not eliminate it.

Introduction of a trench or sheet piling between the track and the MRI would not likely reduce ground vibration at the MRI, because the vibration is likely propagated in the deeper soil or rock strata. This approach could be effective if the tracks were very close to the MRI, in which case most of the vibration energy would be propagated in the upper soil layer. A detailed study of the ground vibration amplitude with depth may yield more information on which to judge the effectiveness of a trench or of sheet piling in reducing ground vibration a the MRI.

The wheels of the hopper cars can be maintained in good condition, without wheel flats, to control both wayside noise and ground vibration. Low vibration levels can be maintained by removing cars with significant wheel flats from service and re-truing or replacing its wheel sets with reconditioned wheels.

CONCLUSION

The measured ground vibration amplitudes for existing railroad operations were usually within the site specifications for the MRI's now employed and proposed to be employed at the Mayo Clinic in Rochester. The ground vibration levels from trains were only modestly higher than existing ambient vibration levels, and then only in the frequency range below about 25 Hz.

Ground vibration produced, apparently, by slack action of the westbound train during braking was in excess of the transient acceleration limit of 500 micro-g. This was the only identifiable event that appeared to be in excess of the site specification for GE MRI's. This type of event may be a common occurrence in Rochester under present rail operations.

The magnitude of ground vibration acceleration generated by slack action events would likely be unchanged with installation of continuous welded rail, though the increased train frequency would tend to increase the number of slack action events.

Root-mean-square ground vibration levels would decrease with installation of continuous welded rail, but would increase with train speed. The rms vibration levels for a train speed of 45 mph would likely be within the vibration limit for the 0.7 Tesla MRI, but in excess of the limit of the 3.0 Tesla MRI, assuming that the random portion of spectral vibration observed during train passage is related to train operation and not background vibration. Project vibration levels would likely be within the vibration limits that have been applied elsewhere for GE 1.5 Tesla MRI's .

If vibration impacts were to occur, mitigation measures might include pile supported slab foundation for the MRI, soil stabilization at the MRI, provision of a straightness specification for new continuous welded rail, using gag pressed rather than roller straightened rail, reducing train speed, and controlling wheel flats. The likelihood of project related continuous ground vibration impacting the MRI's is low. Slack action generated transient vibration after project completion would not likely affect MRI operation if the MRI's are not affected by current train operation.

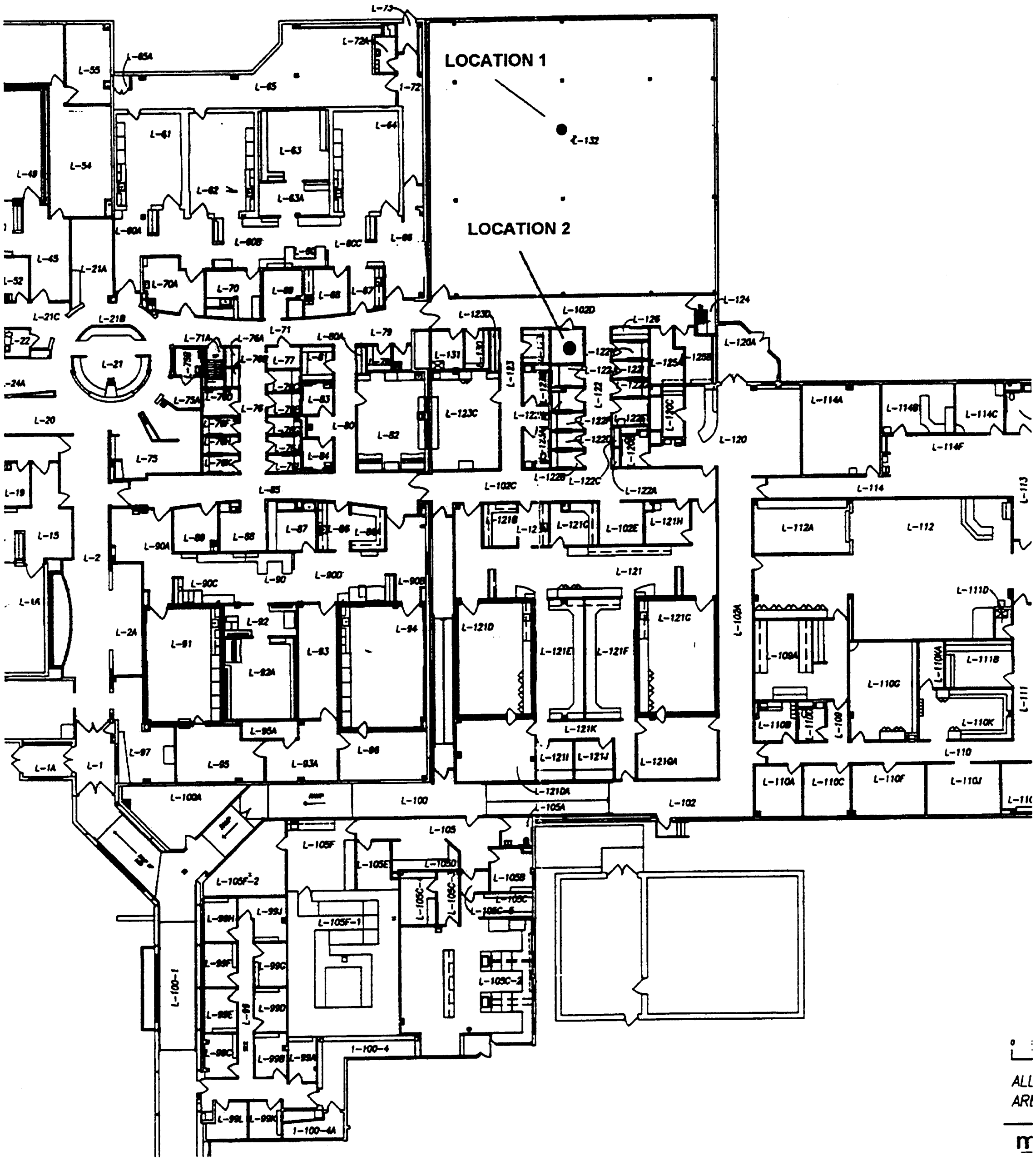

Figure 1 Measurement Locations at Mayo Clinic MRI Facility

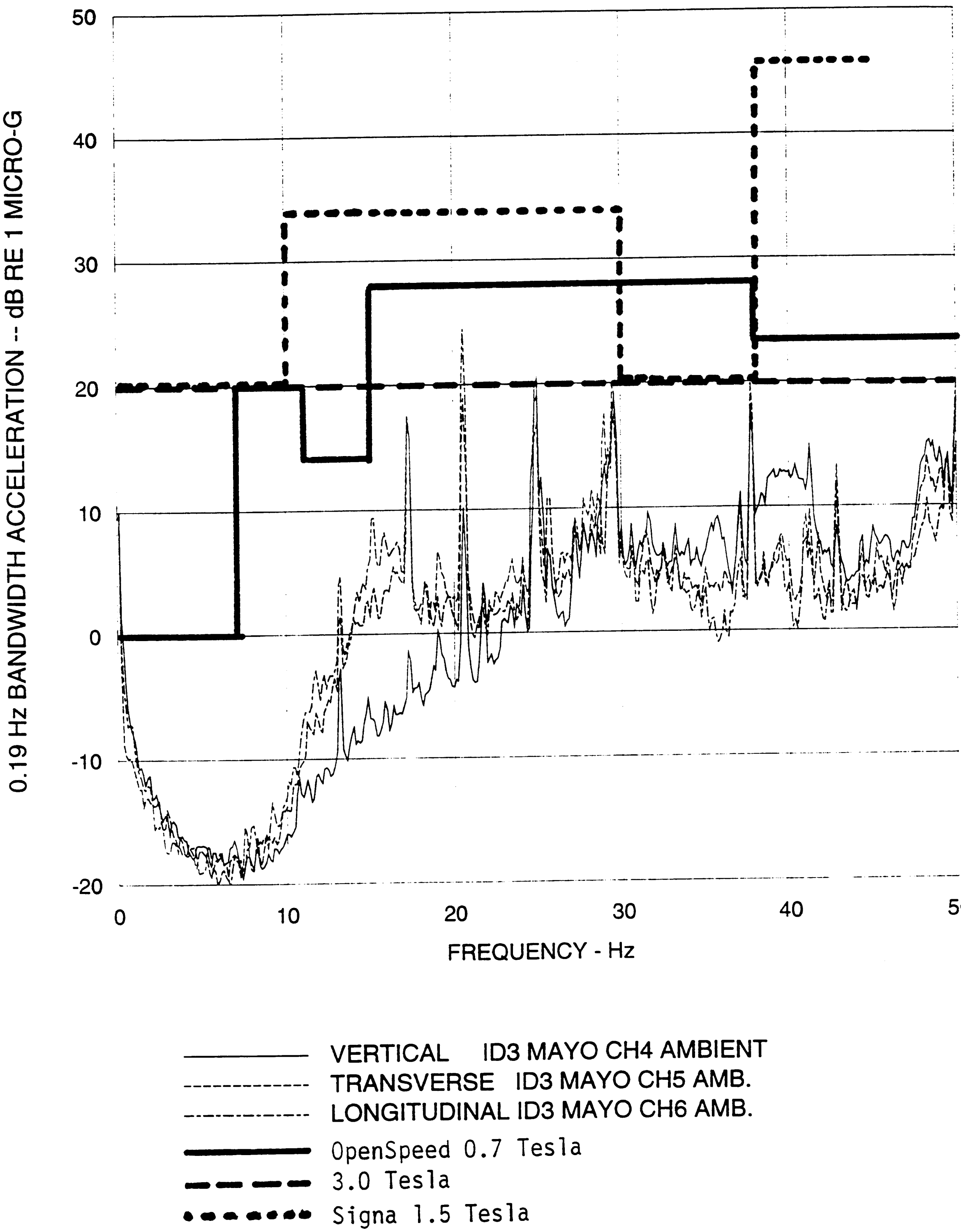

FIGURE 2A AMBIENT GROUND VIBRATION ON SOIL AT PROPOSED MRI SITE AT MAYO CLINIC

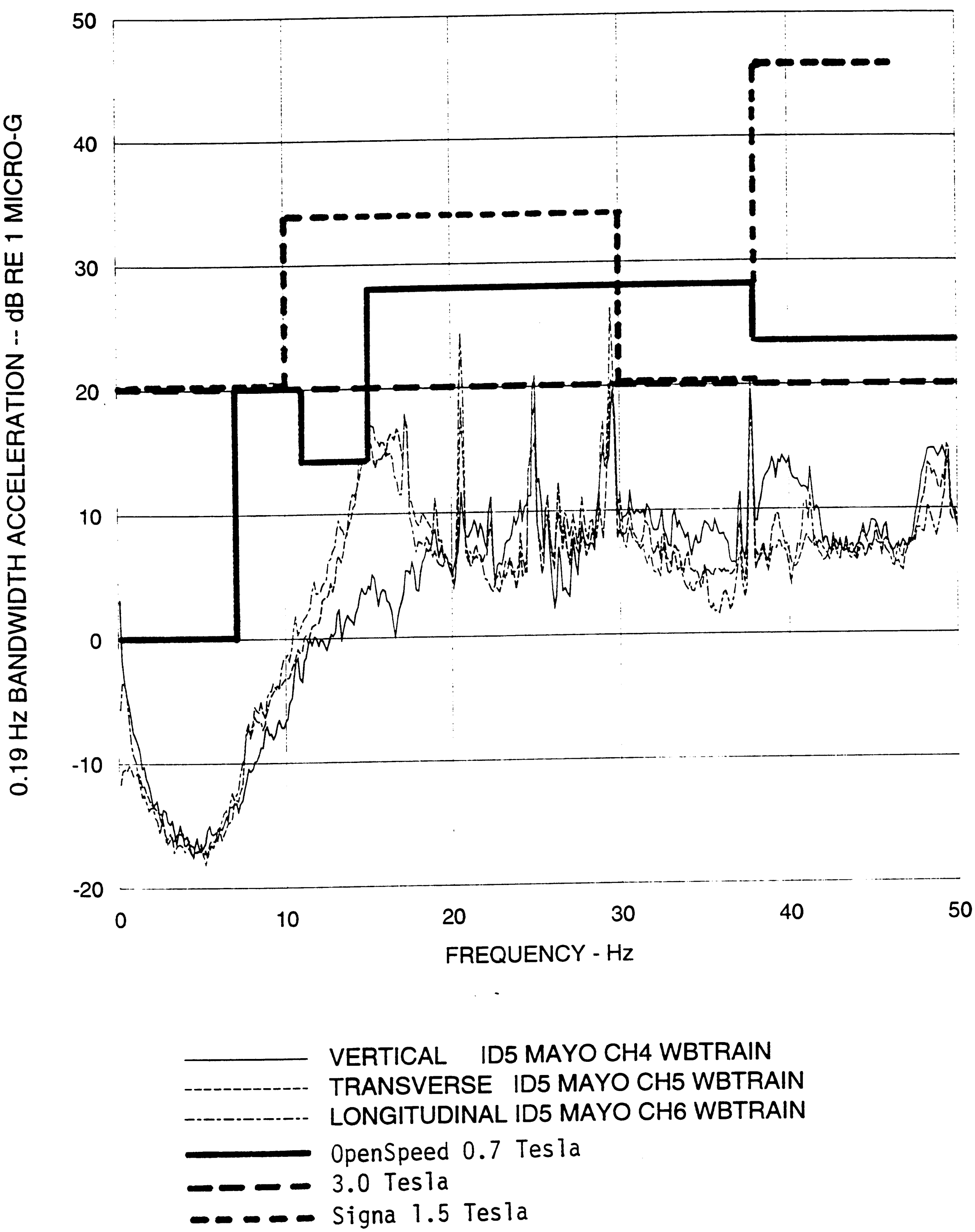

FIGURE 2B WESTBOUND TRAIN GROUND VIBRATION ON SOIL AT PROPOSED MRI MAYO CLINIC

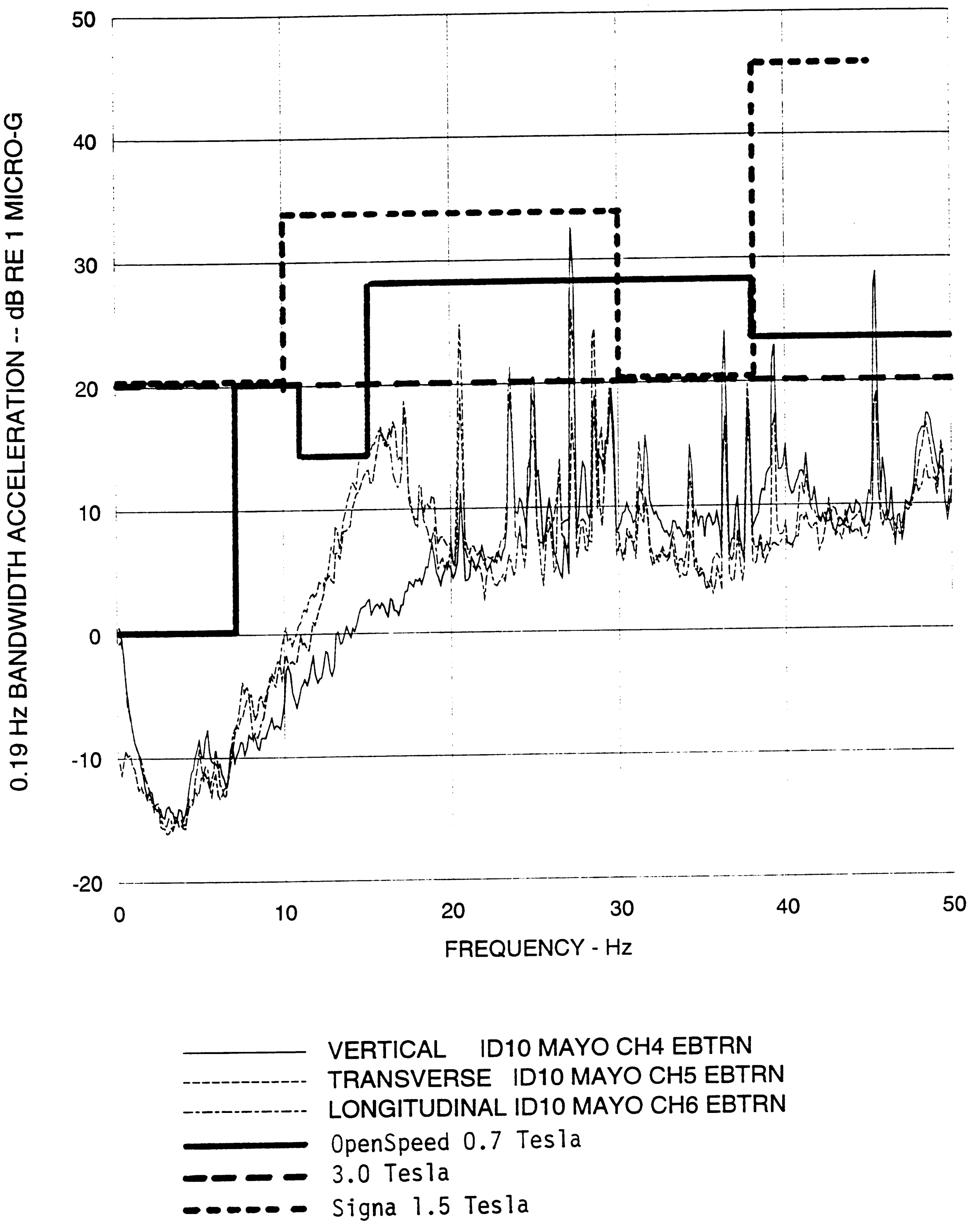

FIGURE 2C EASTBOUND TRAIN GROUND VIBRATION AT PROPOSED MRI SITE MAYO CLINIC

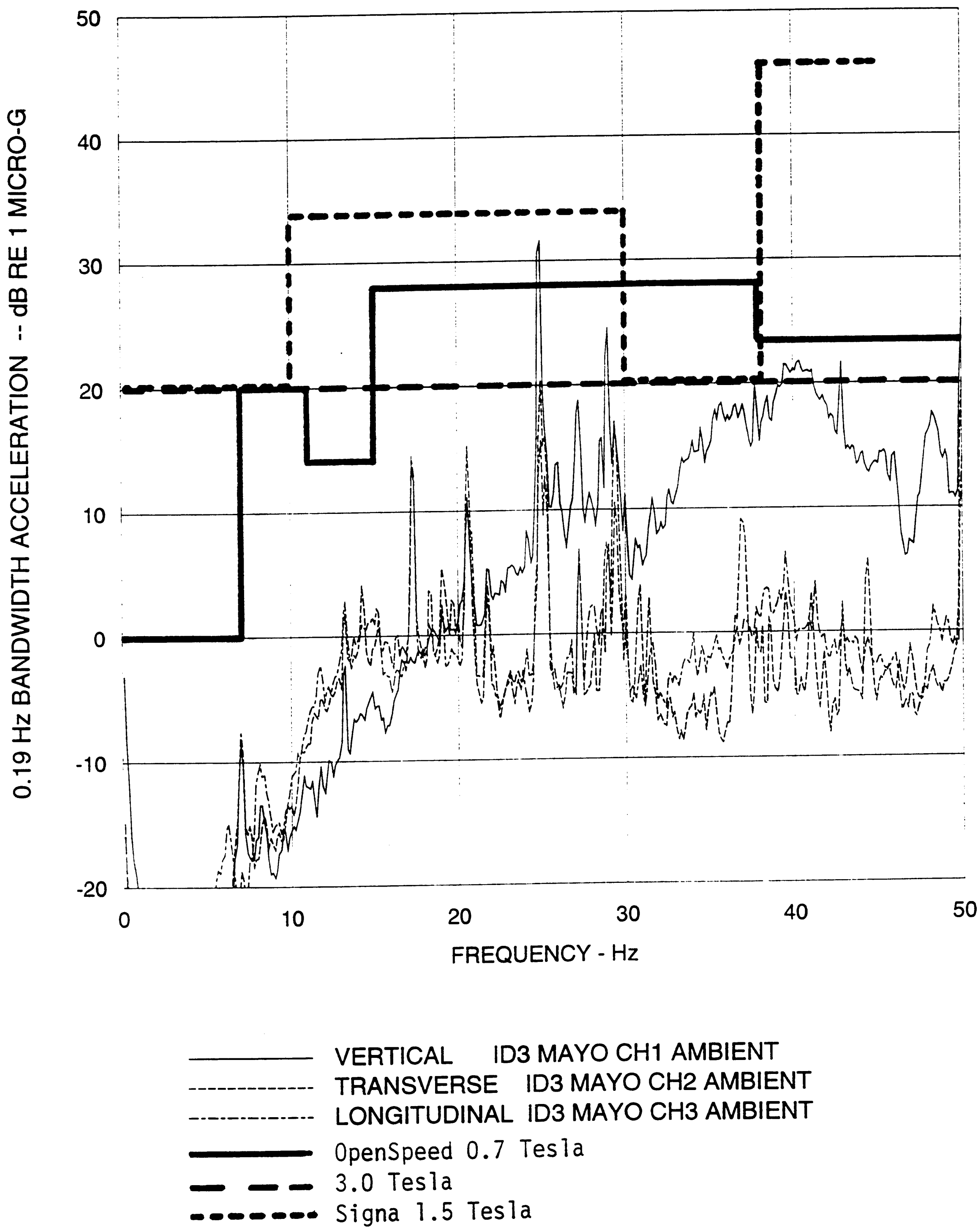

FIGURE 3A AMBIENT GROUND VIBRATION ON CONCRETE SLAB NEAR EXISTING MRI AT MAYO CLINIC

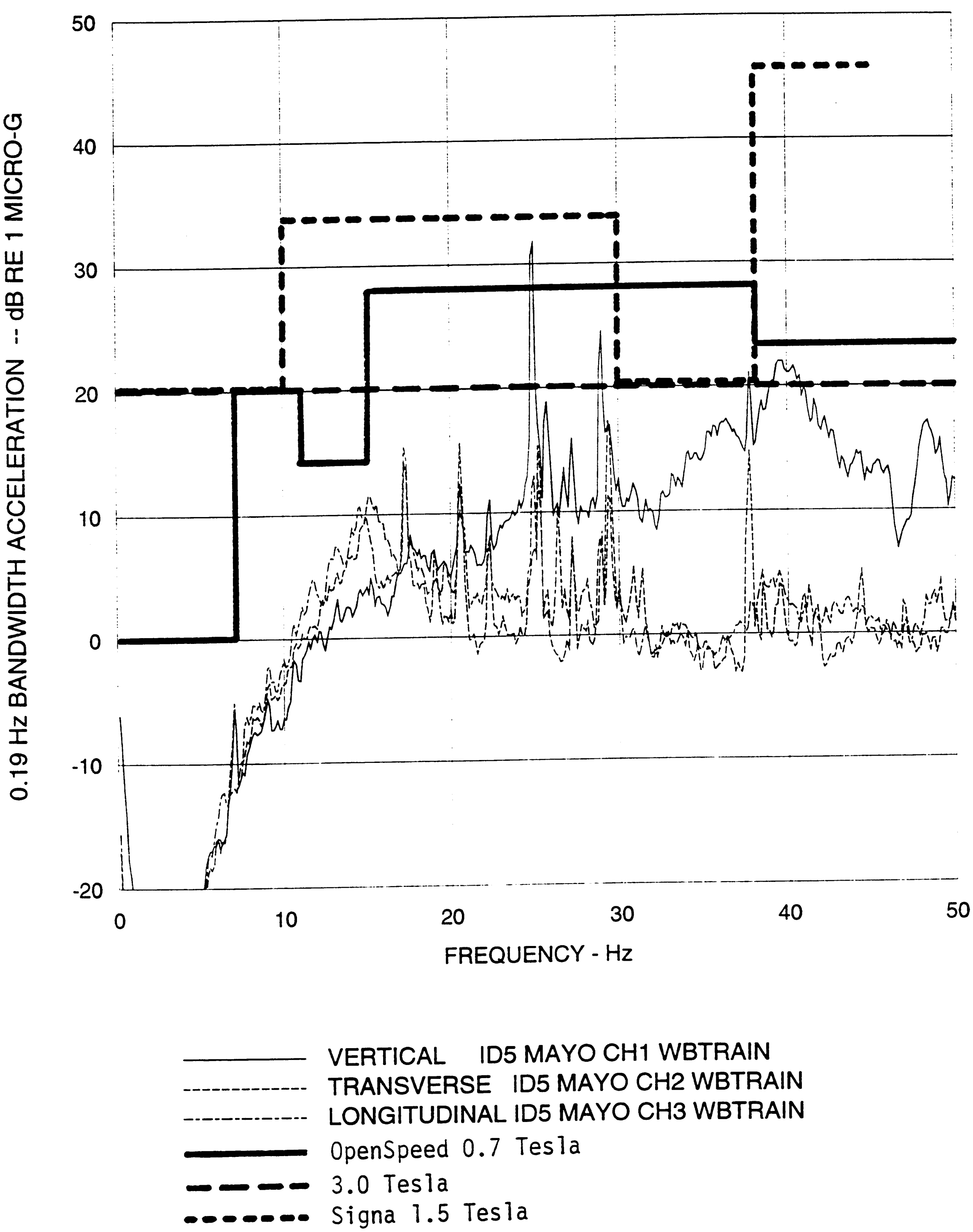

FIGURE 3B WESTBOUND TRAIN GROUND VIBRATION ON SLAB NEAR EXISTING MRI

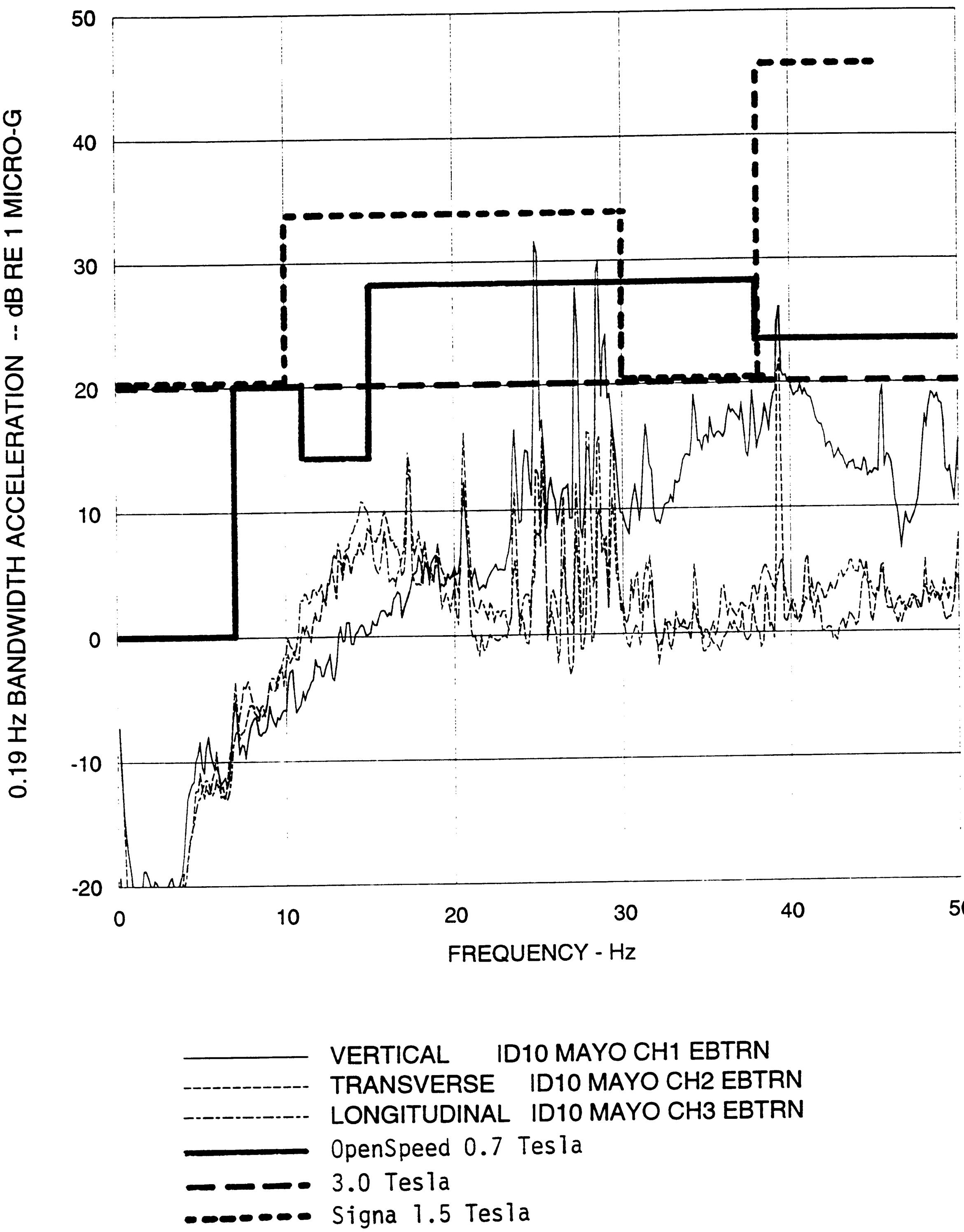

FIGURE 3C EASTBOUND TRAIN GROUND VIBRATION ON SLAB NEAR EXISTING MRI MAYO CLINIC

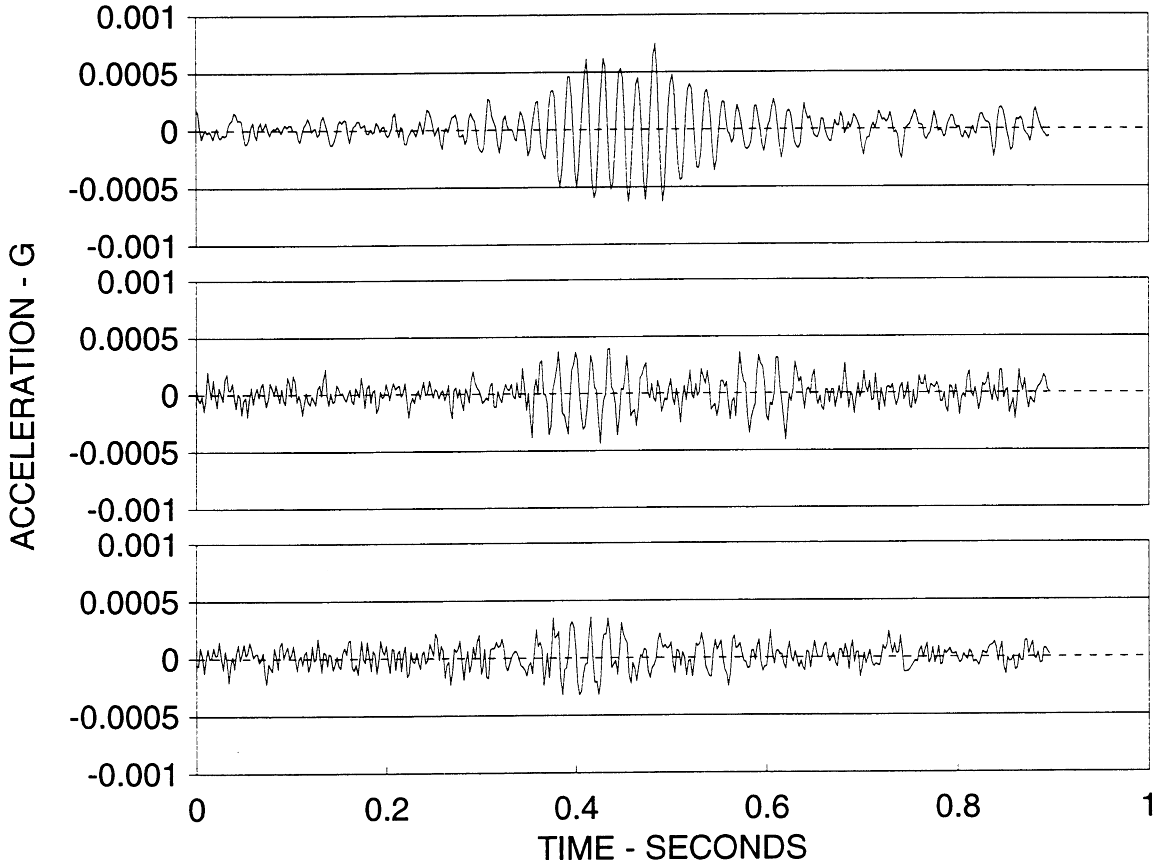

Figure 4 **Ground Vibration Transient at Location 1 during Passage of Westbound Train**

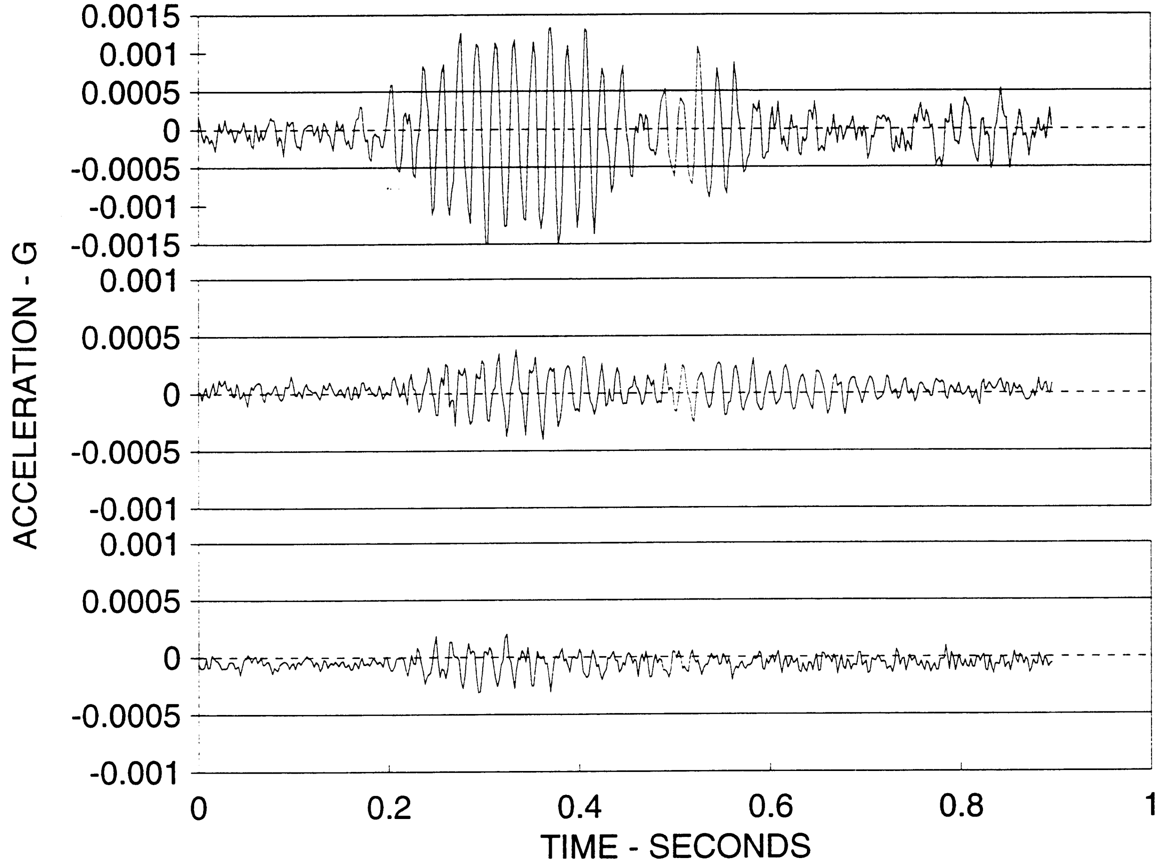

Figure 5 **Transient Acceleration Recorded on Concrete Slab during Passage of Westbound Train**

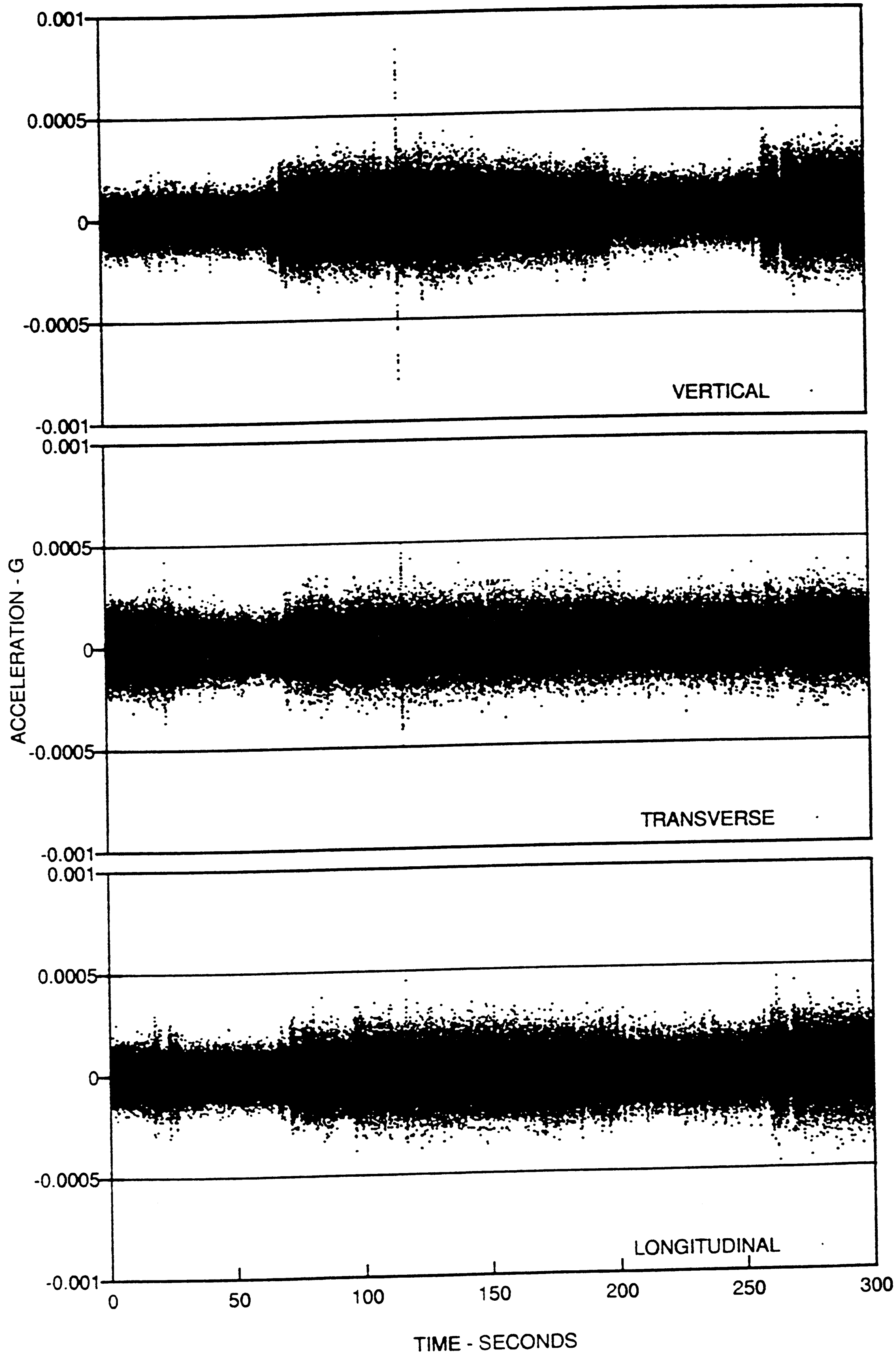

FIGURE 6A AMBIENT GROUND ACCELERATION VS TIME AT LOCATION 1

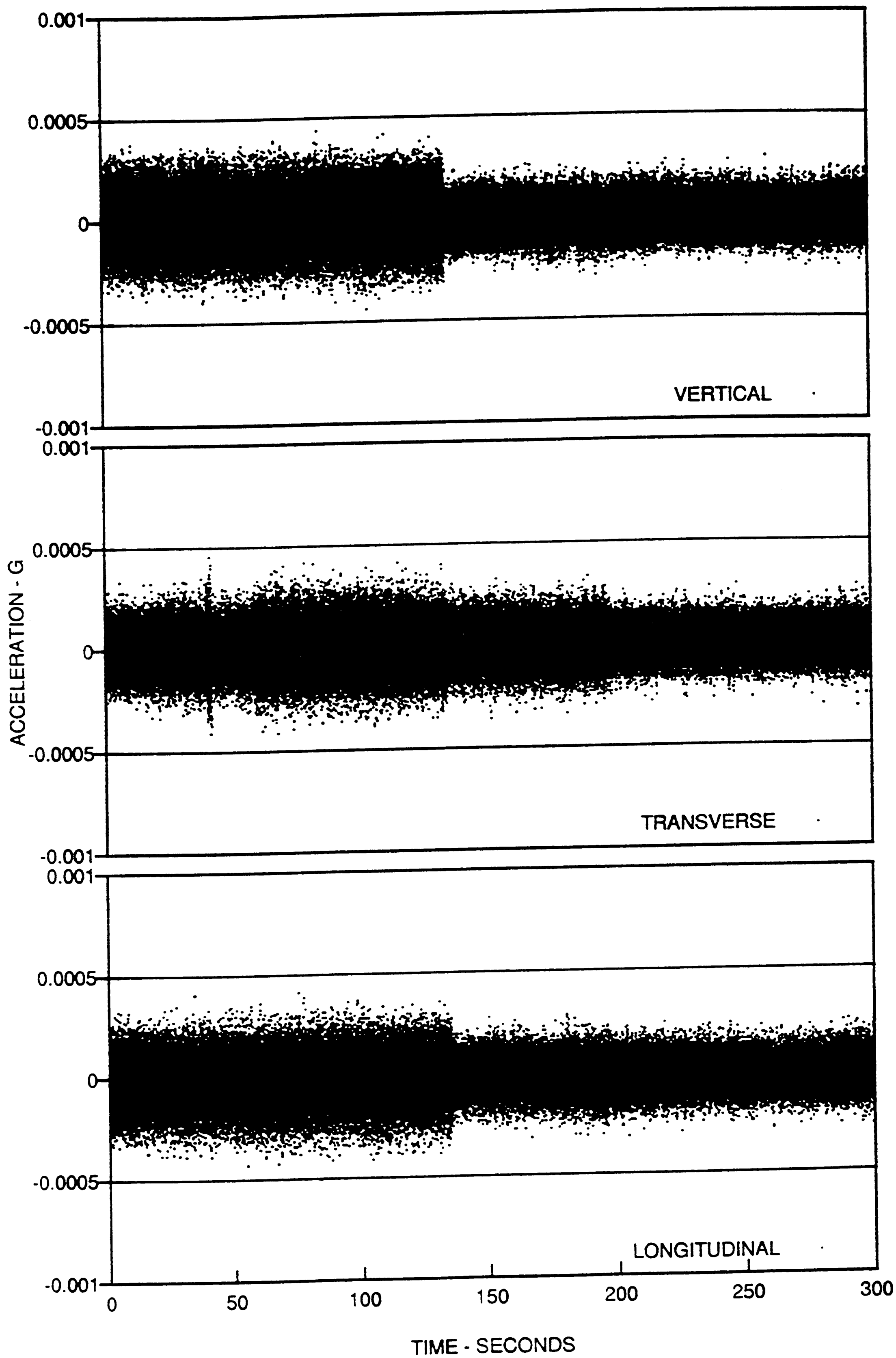

FIGURE 6B GROUND ACCELERATION VS TIME AT LOCATION DURING EASTBOUND TRAIN PASSAGE

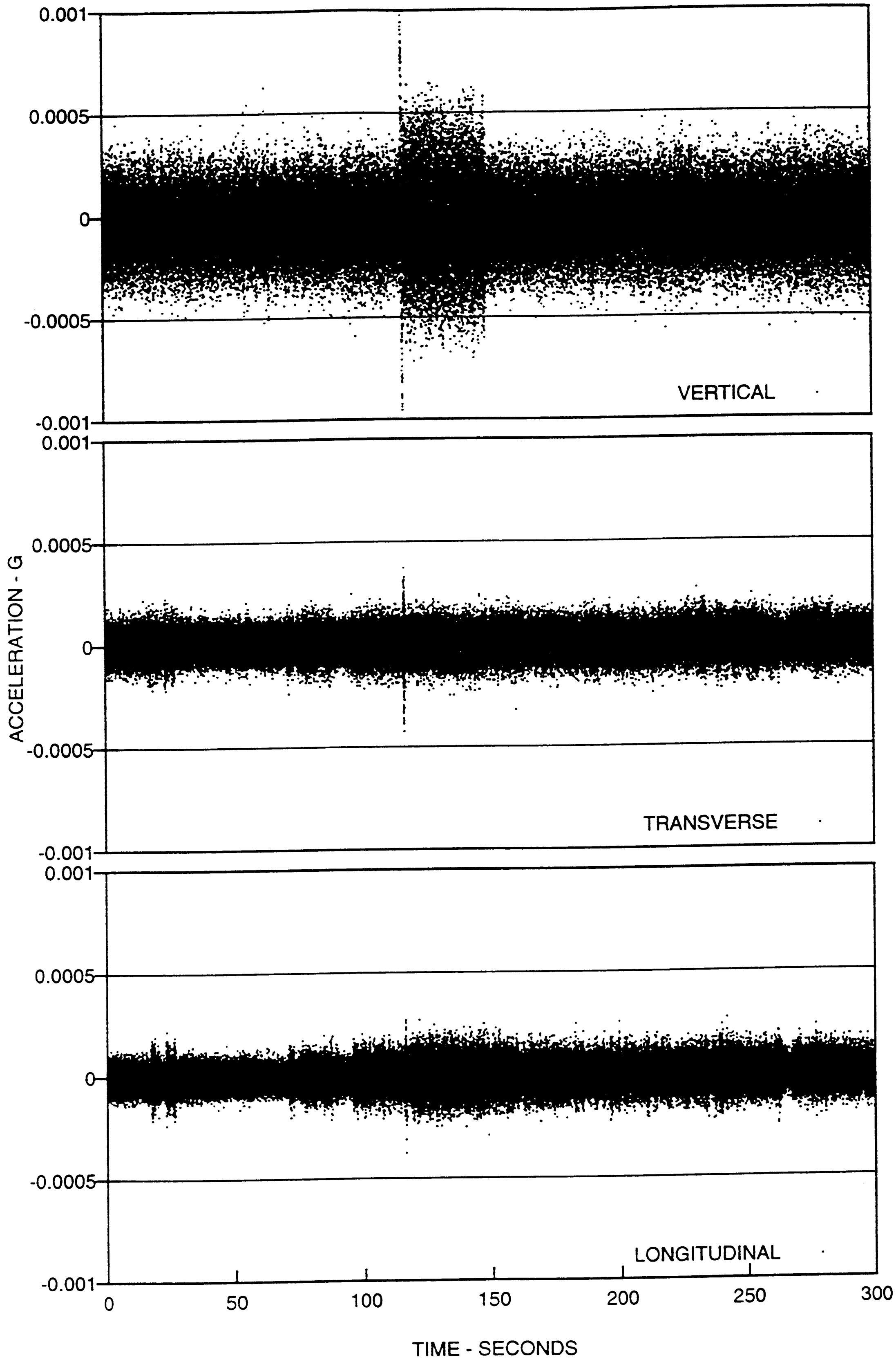

FIGURE 7A AMBIENT FLOOR SLAB ACCELERATION AT LOCATION 2

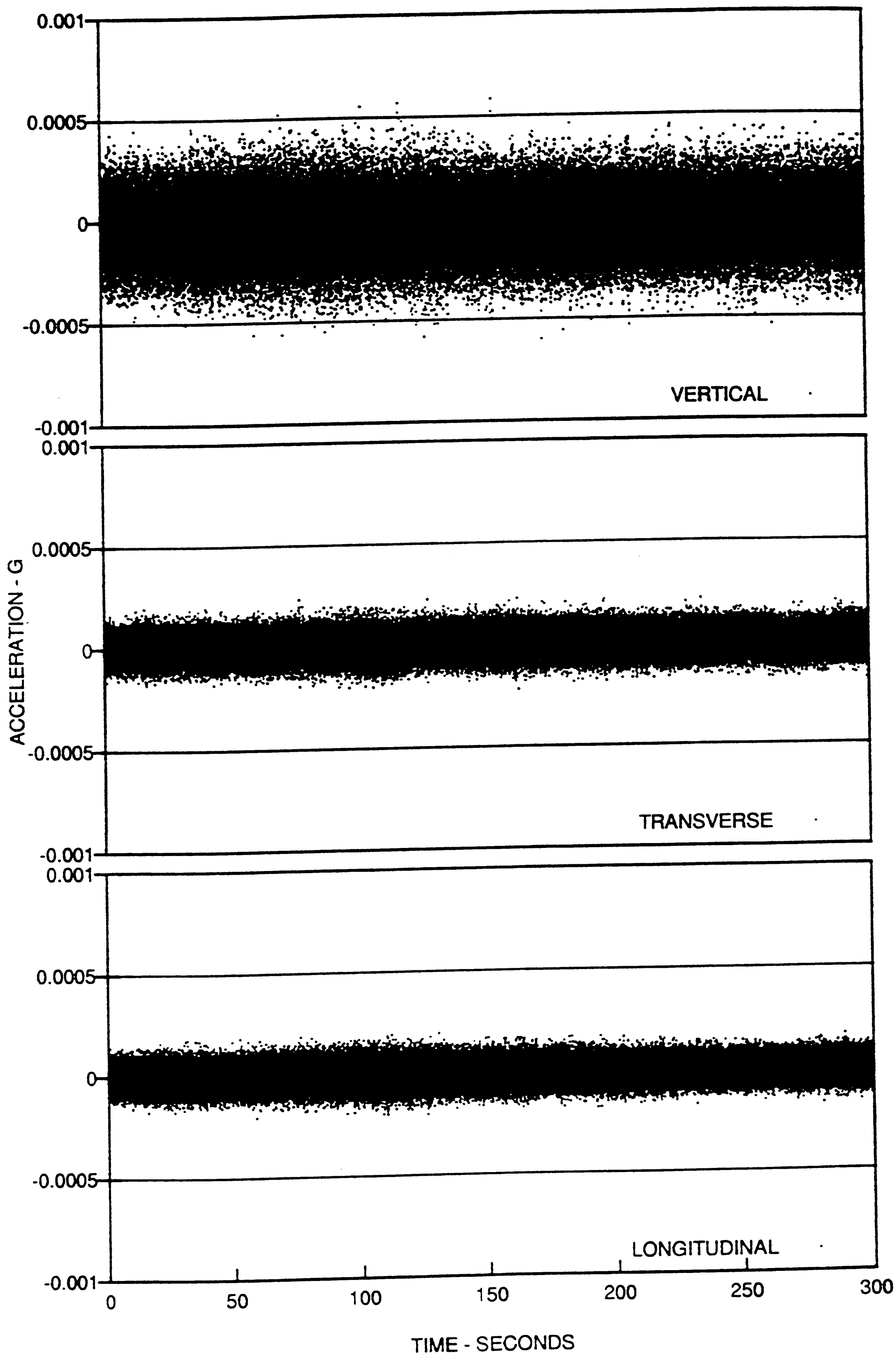

FIGURE 7B FLOOR SLAB ACCELERATION AT LOCATION 2 DURING EASTBOUND TRAIN PASSAGE